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Increased growth of Qinghai spruce in northwestern China during the recent warming hiatus

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ABSTRACT

The effect of warming-induced drought stress on tree growth has been frequently discussed, and a decline in the growth of forest and increased mortality has been reported for many areas of the world. A hiatus in the global warming trend began around the year 2000, but how tree growth has responded to this warming slowdown remains unclear. Here we present a study of the recent impacts of climate change on Qinghai spruce (*Picea crassifolia*) growth using 38 tree-ring records collected from the Qilian Mountains in northwestern China. Results indicate that there was a clear increase in Qinghai spruce growth during the recent warming hiatus. Similarly, regional vegetation growth also improved as indicated by NDVI variations, which is closely associated with regional climate changes. The mean air temperature increased dramatically during the period 1980–2001, whereas precipitation decreased slightly. This combination of warmer temperatures and reduced precipitation created drought conditions that limited the growth of Qinghai spruce during this period. Since 2001, the warming trend has slowed, whereas precipitation has clearly increased, creating moist conditions as reflected by the higher drought index (SPEI). A decline in drought pressure, coupled with an increasingly long growing season, might be the main reason for the recent improvement in the growth of Qinghai spruce in the Qilian Mountains. Our results suggest that the growth of Qinghai spruce is very sensitive to climate change. A better understanding of future climate changes and their likely impact on tree growth should be of significant interest to forest managers.

1. Introduction

Climate change has important implications for forest productivity, carbon stocks, and forest community structure and species compositions because it directly influences tree growth, phenology, vulnerability to disturbance, and so on (Bonan, 2008; Seidl et al., 2017). Many studies have suggested that a warming climate has aggravated the effects of drought stress on forest growth, and drought-induced tree decline and mortality have been reported all over the world (Allen et al., 2010; Worrall et al., 2013; Liu et al., 2013; Hogg et al., 2017; Chen et al., 2017). However, the warming climate has also been shown to lengthen the growing season, accelerating tree growth rates and increasing forest biomass at some sites (Salzer et al., 2009; McMahon et al., 2010; Pretzsch et al., 2014). Thus, climate warming might affect tree growth in diverse ways for different area and tree species.

At the same time, there is debate about the temporal stability of the tree growth response to climate change. At several circumpolar northern latitude sites, a reduction in the sensitivity of tree-ring records to temperature since the mid-20th century has been found to be related to global warming (Briffa et al., 1998; D'Arrigo et al., 2008). The recent global warming hiatus, which began around the year 2000 and has persisted for nearly 15 years (Kosaka and Xie, 2013; Guan et al., 2015), is likely to have had a significant influence on tree growth. However, the effects of this warming slowdown on tree growth remain unclear. A comprehensive study of tree growth response to this hiatus using a large number of tree samples would help shed light on this question, especially in the vulnerably arid and semi-arid regions.

The Qilian Mountains are located in the arid and semi-arid transition regions of northwestern China and at the northeastern edge of the Tibetan Plateau. They stretch from east to west for about 800 km. Climate change, glacier melting and vegetation variations in the Qilian Mountains will significantly influence the oasis farming in the downriver Hexi corridor, which is an important region for China's 'Belt and Road' plan. Qinghai Spruce (*Picea crassifolia*) is an endemic tree species in northwestern China; in the Qilian Mountains, Qinghai spruce as one of the dominant coniferous species, occupying about 20.5% of the forest area and playing an important role in climate regulation, water conservation and the prevention of desertification (Zhang and Zhou, 2003).

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Several climate projections indicate increasing drought intensity, frequency and duration (IPCC, 2013), and accelerated dryland expansion in the arid and semi-arid regions in the coming future (Huang et al., 2016). Therefore, understand how the Qinghai spruce growth respond to the climate change in the Qilian Mountains is critical for ecological and social development in this region.

Several previous studies in the Qilian Mountains have analyzed the spatial variability of Qinghai spruce growth along a latitudinal transect (Liang et al., 2010) and the elevation gradients (Gao et al., 2013; Zhang et al., 2017a). These studies suggest that moisture availability is a dominant limiting factor for tree growth in this area. In the central Qilian Mountains, a decline in Qinghai spruce tree growth and an increasing in tree mortality has been reported for several high elevation sites (Liang et al., 2016). At the same time, an increase in the growth of Qinghai spruce has been attributed to warming temperatures and a reduction in the frequency of frost during the growing season at a high elevation site in the eastern Qilian Mountains (Waring and Gao, 2016). In addition, some previous studies indicate that the decline of Qinghai spruce growth since the 1980 s is due to accelerated warming (Li et al., 2015). However, because global warming paused after 2000 for almost 15 years (Guan et al., 2015), we hypothesize that the growth of Qinghai spruce should show signs of recovery in response to the warming hiatus and reduction in drought stress.

In this study, we investigated the impacts of climate change on Qinghai spruce growth using tree-ring data collected from 38 plots in the Qilian Mountains. We aim to 1) assess the tree growth patterns and responses to the climatic shift from warming to a warming hiatus, as well as to precipitation and drought variations; 2) analyze the climate-growth relationships of Qinghai spruce with climate change; 3) evaluate the regional vegetation variation tendency and provide some insights for future forest management.

2. Data and methods

2.1. Study sites

On the north side of the Qilian Mountains, 38 studied plots were selected along a northwest-southeast transect, with an average distance from one plot to the next of about 20 km (Fig. 1a). The elevation of the Qilian Mountains increases gradually from southeast to northwest, with a maximum elevation of 5808 m in the northwest of the range. For the period 1961–2015, the mean annual temperature in the study sites ranged from −7.1 °C to 7.6 °C, which is strongly related to elevation (Fig. 1b). The total annual precipitation varied from 109 mm to 588 mm, with the central-eastern part of the mountains receiving the most moisture (Fig. 1c). The majority (79%–91%) of the annual precipitation occurred between May-September, which is also the warmest period of the year. Qinghai spruce is a cold- and shade-tolerant species that is usually found on north facing slopes. This species is mainly distributed at elevations ranging from 2500 to 3500 m a.s.l (Zhao et al., 2008). Pure Qinghai spruce forests are very common in this area, with high canopy closure and few understory shrubs.

2.2. Tree-ring data

We conducted the tree-ring sampling work in the autumn of 2016. 38 pure Qinghai spruce forest stands were carefully selected in areas with light human activity. The elevations of these sampling plots ranged from 2655 m to 3140 m a.s.l. (see details in Supplementary Table S1). For each stand, a 20 m × 20 m sampling plot (or 25 m × 25 m for some stands with sporadic and large trees) was deployed, and 25–39 trees were randomly selected and sampled. Two cores were extracted from different directions for each tree at a height of about 50 cm above the ground. In a few cases (27 trees), the extracted cores run through the transversal surface of the tree. We measured the two sides of these cores to help with cross-dating and to get more useful tree-ring series. In total, 2349 tree-ring cores from 1161 Qinghai spruce trees were collected for this study.

All of the tree cores were taken to the laboratory and processed according to the standard techniques of dendrochronology (Stokes and Smiley, 1968). After being air-dried and mounted, tree cores were polished with sandpaper until all rings were clearly visible under the microscope. We then dated every ring and measured ring-widths using the Velmex measuring system with a precision of 0.001 mm. The COFECHA and TSAP programs were applied to check the quality of cross-dating (Holmes, 1983; Rinn, 2003). The computer program ARSTAN was used for detrending and for calculating the tree-ring chronologies (Cook et al., 2013). Conventional straight lines and negative exponential curves were used to detrend most of the tree-ring series, but a cubic smoothing spline with a 50% frequency response cutoff equal to 67% of the series length was used in a few cases if the previous two curves did not provide a good fit. Finally, 38 standard chronologies were developed for the subsequent analysis. To verify the growth trend of Qinghai spruce indicating by the tree-ring chronologies, we also calculated the basal area increment (BAI) from the ring widths using the Dendrochronology Program Library in R (dplR, Bunn, 2008).

2.3. Climate data

Several kinds of climate data were used to explore the climate variations and the climate-growth relationships, including precipitation (monthly), temperature (monthly and daily), and the Standardized Precipitation Evapotranspiration Index (SPEI;Vicenteserrano et al., 2010). Because publicly available weather stations are sparse and generally far from the sampling sites in this region, gridded climate data with a spatial resolution of 0.5° × 0.5° was used in this study. The precipitation and temperature datasets were downloaded from the China Meteorological Data Service Center (CMDC; http://data.cma.cn/). These datasets were developed from quality- controlled observational data from 2472 gauges located throughout mainland of China and in operation since 1961. The data were interpreted to a 0.5° × 0.5° grid with the ANUSPLIN software using the thin plate smooth spline method. Because there were some missing values for the years 2015 and 2016, we used monthly data from 1961 to 2015 and daily data from 1961 to 2014. The daily mean temperature was used to compute the number of days with a daily temperature higher than 5°C, which was referenced as the length of the growing season. This is because Qinghai spruce growth usually begins in May (Tian et al., 2017), when temperatures are about 5°C on average. The SPEI data utilized in this study were obtained from the SPEI base version 2.5 (Beguería et al., 2010; available at http://sac.csic.es/spei/database.html), which was calculated from the CRU TS 3.24.01 dataset. For this study, we used the SPEI at the 12-month scale for the period 1961–2015.

2.4. NDVI data

To investigate variations in the satellite-derived regional vegetation greenness over the last several decades, the biweekly Normalized Difference Vegetation Index (NDVI; obtained from the GIMMS team; https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v1/; Pinzon and Tucker, 2014) was used in this study. This updated NDVI dataset has a spatial resolution of 1/12° and spans the period from 1981 to 2015. However, as the records for 1981 are incomplete, we used just the data from 1982 to 2015 for this analysis. The maximum value at each grid point for each year was used, and only the grid points with a mean annual NDVI larger than 0.1 were applied in the analysis to exclude no or sparsely vegetated grid points. Differences in the NDVI between the 1990 s and the 1980 s were calculated, as were the differences between the 2000 s and the 1990 s, and the 2010 s and the 2000 s.

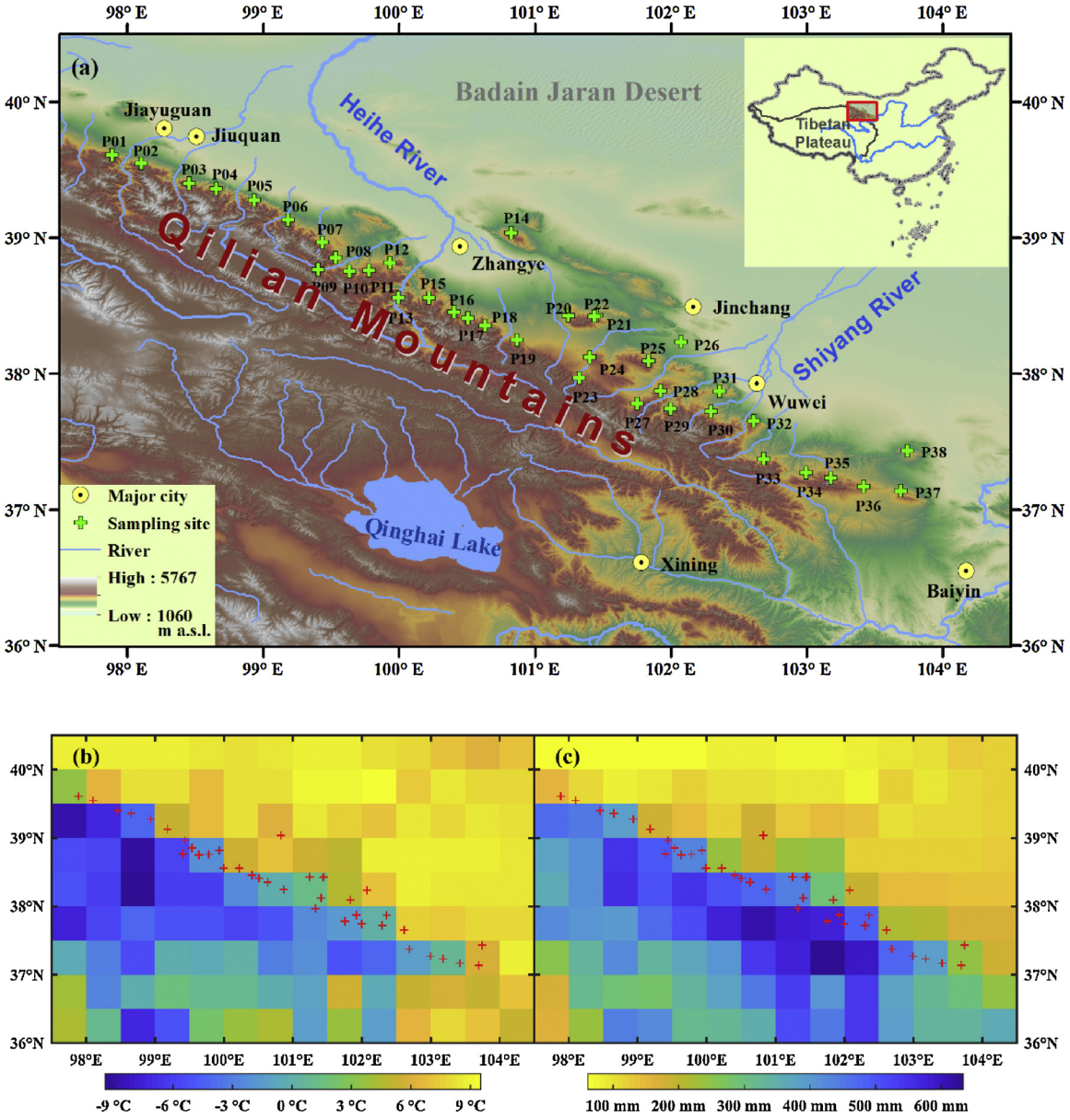

Fig. 1. Study area and distribution of the 38 tree-ring sampling plots (green crosses) on a digital elevation map, with the plot number (P01 to P38) increasing from northwest to southeast across the Qilian Mountains (a). The gridded annual mean temperature (b) and total annual precipitation (c) in the study area for the period 1961–2015. Only the gridded climate data that with the tree-ring sampling plots (red crosses in (b) and (c)) inside the grids were used in this study.

2.5. Statistical analyses

We calculated several statistical parameters for the 38 chronologies to investigate the tree growth patterns across different geographical areas. Mean sensitivity indicates the year-to-year changes in tree-ring growth; the mean inter-series correlation represents the average of the correlations between all tree cores from one sampling plot. The sub-sample signal strength (SSS) > 0.85 was used to determine the robust chronology length, or the period for which, enough samples are available that the chronology can be considered reliable (Wigley et al., 1984). The mean ring width, percentage of absent rings and the signal-to-noise ratio (S/N) were also calculated. Principal component analysis (PCA) was performed using the MATLAB R2014b to calculate the first principal component (PC1) of the chronologies and BAIs.

To assess the climate-growth relationships, Pearson correlation analysis and moving correlation calculations were performed using the MATLAB R2014b. Correlations between the tree-ring chronologies and climate variables (temperature, precipitation and SPEI) were tested for the period 1961-2015. For each chronology, the nearest gridded climate data were employed to compute the correlations over an 18-month window from May in the previous year to October in the current year. Other periods, such as the prior July to current June and May-August of the current growing season, were also examined. To reduce the influence of common trends between chronologies and climate variables, particularly for the temperature data, the first order difference calculations were applied for both the chronologies and the climate data. To determine the main climatic factors limiting tree growth, we also calculated the proportions of chronologies that correlated significantly ($p < 0.05$) with the climate variables for each month.

3. Results

3.1. Geographical patterns of Qinghai spruce growth in the Qilian Mountains

The statistical parameters of the chronologies suggest differences in

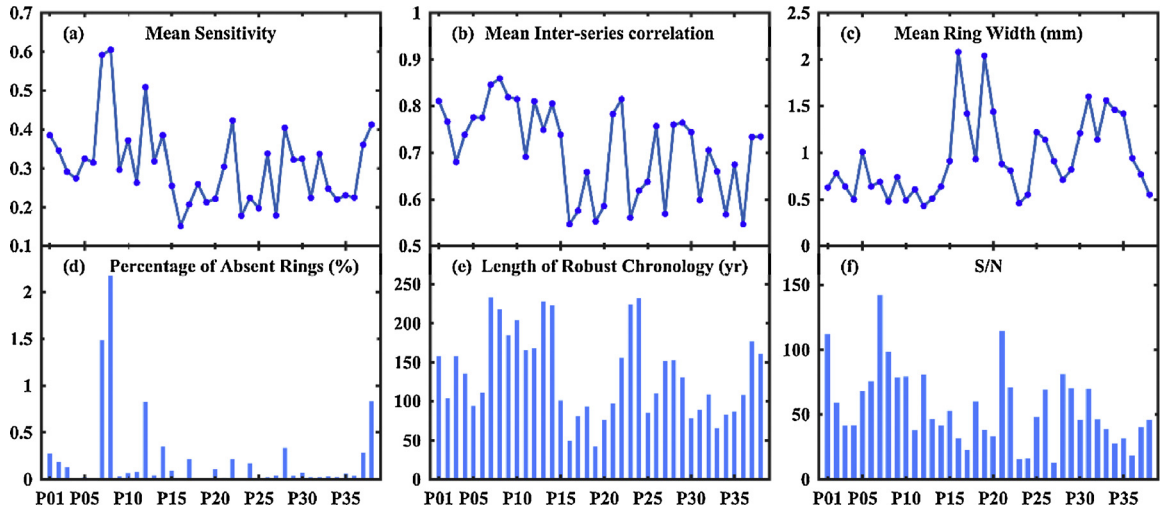
(a) Mean Sensitivity
(b) Mean Inter-series correlation
(c) Mean Ring Width (mm)
(d) Percentage of Absent Rings (%)
(e) Length of Robust Chronology (yr)
(f) S/N
P01 P05 P10 P15 P20 P25 P30 P35

Fig. 2. Some statistical parameters used to explore the differences in the growth of Qinghai spruce across the Qilian mountains. The parameters include the mean sensitivity (a), mean inter-series correlation (b), mean ring width (c), the percentage of absent rings (d), the length of robust chronology (e), and the signal-to-noise ratio (S/N, (f)).

tree growth patterns over large geographical areas. Because we conducted the field work in the Qilian Mountains from west to east, the plot number is roughly indicative of the sampling location, with small numbers in the western part of the range and large numbers in the eastern part of the range (Fig. 1). As shown in Fig. 2, we found that the mean sensitivity (Fig. 2a), mean inter-series correlation (Fig. 2b), and signal-to-noise ratio (Fig. 2f) were much higher at sites in the western part of the range than at sites in the middle and eastern parts of the mountains. For P16 and P19, the lengths of the robust chronologies were less than 50 years (Fig. 2e), and the mean ring widths were exceedingly high (Fig. 2c). With the exception of these two sites (P16 and P19), the mean ring width generally increased from the west to east across the Qilian Mountains (Fig. 2c). The percentage of absent rings was much higher at P07 and P08 than at other plots (Fig. 2d). The lengths of the robust chronologies for these sites suggest that trees in the middle-west part of the mountains are older; trees from plots P15-P20 were much younger (Fig. 2e). Overall, Qinghai spruce trees from the western Qilian Mountains grow slower (narrower rings and older ages) and are more sensitive to environmental variations (high percentage of absent rings and S/N) than trees from the eastern part. This means that trees from the western Qilian Mountains should be more sensitive to climate change and are thus appropriate for dendroclimatological studies.

3.2. Tree growth trends and patterns reflected by the tree-ring chronologies and BAIs

Because the common period of the 38 tree-ring chronologies is from AD 1975–2016, and because most of the climate stations in the study area were installed after 1960, we focus our study on the recent six decades. We calculated the cross-correlations among the 38 chronologies (Supplementary Fig. S1) and compared the variations in the tree-ring chronologies. The cross-correlations suggest high correlations between chronologies, whereas the chronologies from plot P16, P19 and P23 suggest low positive and even negative correlations with others. Given that these three chronologies are quite different from others (Supplementary Fig. S2), which were excluded from the next climate-growth relationships analysis. The PC1 of the remaining 35 tree-ring chronologies were extracted to represent the trees' growth patterns (Fig. 3a, b), which account for 47% of the variations in the tree-ring records. The PC1 of the BAIs (Fig. 3c, d), which account for 45% of the variations in the 35 BAIs series, shown significant ($p < 0.05$) increase trends in the period 1960–1980 and 2001–2016, and significant ($p < 0.01$) decline in the period 1980–2001. Meanwhile, the means of 35 tree-ring chronologies and BAIs also represent the similar variation patterns with the PC1s. The trends and patterns reflected by the tree-ring chronologies and BAIs suggest that there was a clear increasing growth trend of Qinghai spruce during 1960–1980. After 1980, there is a clear decline in tree growth until 2001. Since 2001, the tree growth increased again.

3.3. Climate variations in the study area during the past six decades

Fig. 4 shows the climate variations in the study area over the past six decades, including the annual mean temperature, annual total precipitation, the SPEI at the 12-month scale, and the number of days per year with a daily mean temperature higher than 5 °C. We found that temperature did not change significantly between 1961 and 1980, but there that abrupt and significant increases in temperature occurred during the period 1980–2001, with a rate of increase of 0.68 °C/decade (Fig. 4a). Since 2001, this rate of increase has slowed, which is consistent with the global warming hiatus reported by other studies (Kosaka and Xie, 2013; Guan et al., 2015). There was a clear increasing trend in precipitation from 1961 to 2015, and most of the increases occurred after 2000 (Fig. 4b). Variations in the SPEI indicate the regional changes in climate, with a wetting trend in 1961–1980, then drying trend from 1980 to 2001. For the last 15 years, in parallel with the warming hiatus, the regional climate has tended to be wet again (Fig. 4c). The number of days per year with a daily mean temperature higher than 5 °C- was applied here to represent the length of the growing season for Qinghai spruce growth, which is highly related to variations in the temperature. The results indicated that the length of the growing season has increased dramatically over the past six decades. Since 2000, the mean growing season length is about 10 days longer than it was during the period 1961–1980 (Fig. 4d). All the results above indicate that the climate in the study area has changed significantly over the past six decades, a change that is likely to have significantly affected regional tree growth.

3.4. The impacts of climate change on tree growth and on climate-growth relationships

Pearson's correlations between the tree-ring chronologies and the climate variables were calculated to examine the main climatic factors affecting Qinghai spruce growth. As shown in Fig. 5, there were very similar correlation patterns for these tree-ring chronologies with the

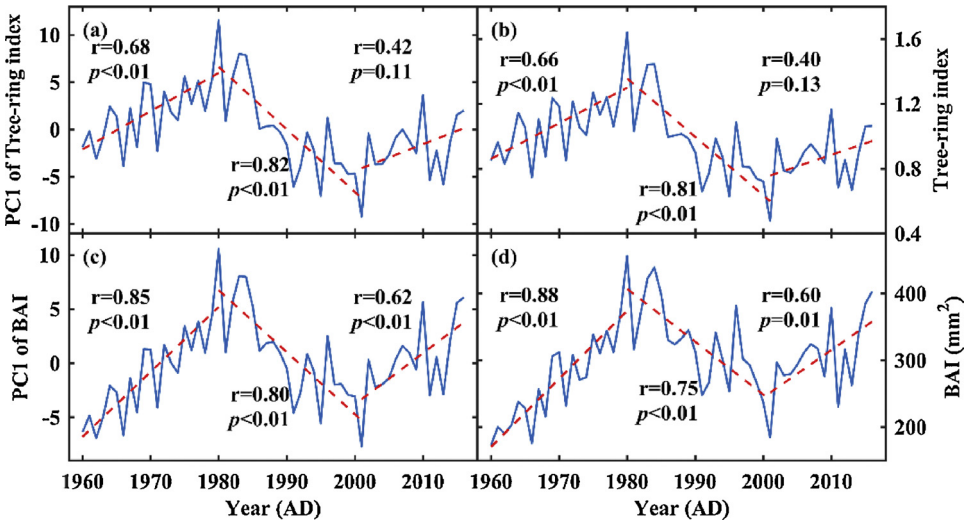

Fig. 3. The variations of tree-ring records and BAIs during the period 1960-2016. (a) The PC1 of the 35 tree-ring chronologies (not include the P16, P19 and P23 because of the short records and different patterns), which account for 47% of the variations in the tree-ring records; (b) the mean of the 35 tree-ring records; (c) the PC1 of the 35 BAIs series, which account for 45% of the variations in the 35 BAIs series; (d) the mean BAI for the 35 tree-ring sites. The red dash-lines in plots indicate the linear trends during the periods 1960–1980, 1980–2001 and 2001–2016, respectively.

climate variables. Most chronologies exhibited significantly negative correlations with temperature in July of the previous year and in June of the current growth year (Fig. 5a, d). The correlation coefficients were even higher for the data without the first order difference calculations (Supplementary Fig. S3). Strong correlations with precipitation were found for August and September in the previous year, as well as for the current spring and early summer (Fig. 5b, e). Almost all of the tree-ring chronologies correlated positively with the precipitation from prior July to current June (Fig. 5e). The correlations between tree-ring chronologies and SPEI suggest some differences across geographic and microclimatic regions, but most showed strong positive correlation between May and August (Fig. 5c, f). This means that the growth of Qinghai spruce in the Qilian Mountains is mainly limited by dry climatic conditions during the growing season.

To investigate the stability of climate-growth relationships under the climate changes, moving correlations were calculated between the tree-ring chronologies and main climatic factors limiting tree growth (Fig. 6), namely temperature in prior July and current June, precipitation from July in the previous year to June in the current year, and the May-August SPEI. The results indicate small variations in the moving correlations with temperature in prior July (Fig. 6a, e), but significant changes over the past six decades in the correlation between tree growth and temperature during the current June. The number of chronologies that correlated significantly with current year June temperature increased dramatically during the 1980 s and 1990 s, then decreased in the 2000 s (Fig. 6f). For the moving correlations with precipitation (Fig. 6c), the number of chronologies that correlated significantly with precipitation from prior July to current June decreased slightly since the 1960 s (Fig. 6g). This is likely associated with the wetting trend observed in the study area (Fig. 4b). There was an abrupt increase in the number of chronologies that correlated significantly with the May-August SPEI during the 1980 s and 1990 s (Fig. 6h), suggesting that tree growth was limited by drought conditions during that period.

Overall, the most obvious change in the climate-growth relationships was the correlation between the tree-ring chronologies and June temperature, which indicates that temperature variations during the past six decades have had an unstable influence on regional tree growth. Temperature increased significantly during the 1980 s and 1990 s (Fig. 4a), which resulted in a notable negative effect on tree growth. With the warming hiatus and precipitation increasing since the 2000 s, the warming-induced drought stress on tree growth was mitigated and the number of tree-ring chronologies that correlated significantly with SPEI decreased.

3.5. NDVI variations during the period 1982–2015

To explore the effects of climate change on overall regional vegetation growth, NDVI variations during the period 1982–2015 were investigated. The results indicate that the NDVI generally decreased in 1990 s at the tree-ring sampling sites compared to the 1980 s (Fig. 7a), which is in line with the decline in tree growth recorded by the tree-ring

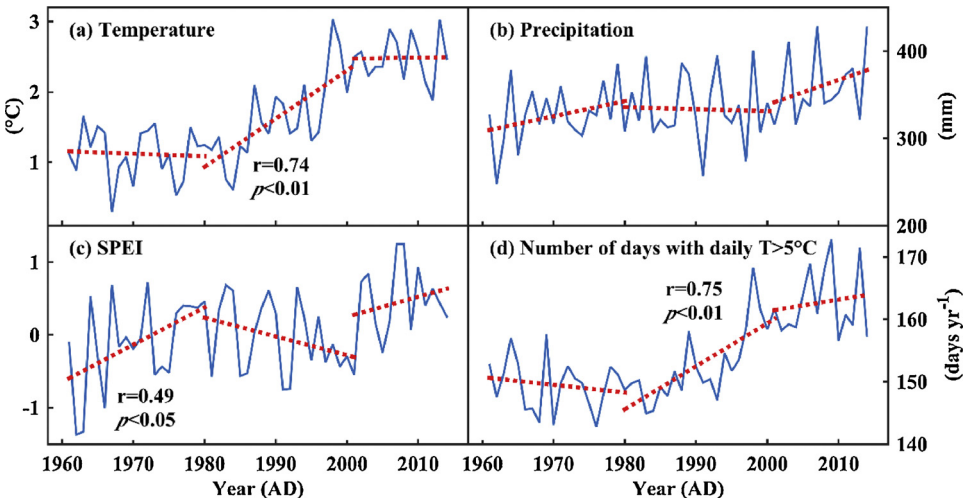

Fig. 4. The annual mean temperature (a), total annual precipitation (b) and the Standardized Precipitation Evapotranspiration Index (SPEI) at the 12-month scale (c) for the period 1961–2015; (d) shows the number of days per year with a daily mean temperature higher than 5 °C during 1961-2014. The red dotted lines indicate the linear trends of these climate variables during the periods 1961–1980, 1980–2001 and 2001–2015/2014, respectively.

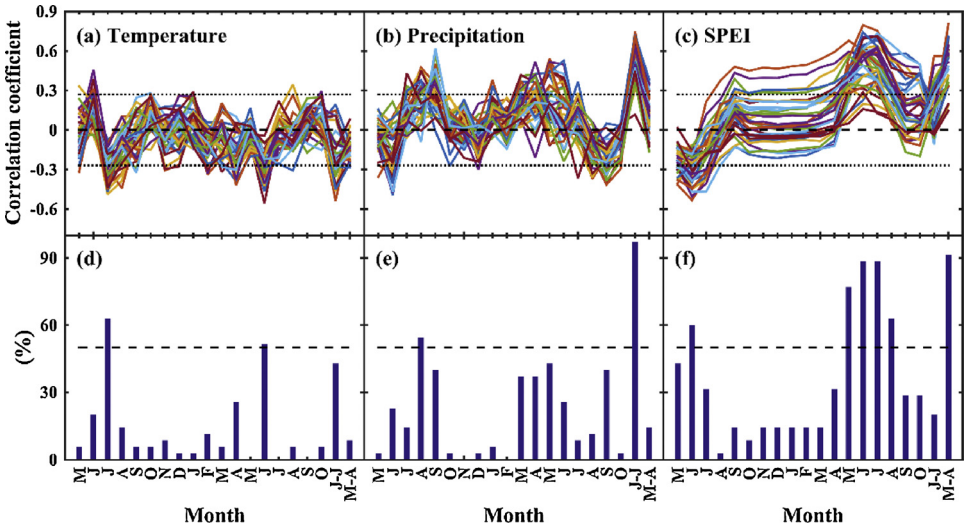

Fig. 5. The correlations between tree-ring chronologies and the climate variables (temperature (a), precipitation (b) and SPEI (c)) over an 18-month window from May of the previous year to October of the current year, as well as for prior July to current June (J-J) and May-August in the current growing season (M-A). The dotted lines represent the 95% confidence level. A first order difference calculation was applied to both the tree-ring chronologies and the climate data to avoid the influence of low-frequency variation on correlations. The bottom plots (d, e, and f) indicate the percentage of chronologies that correlated significant ($p < 0.05$) with the climate variables for each month, with the horizonal dash-lines represent the value of 50%.

chronologies (Fig. 3). In comparison to the NDVI in the 1990 s, the NDVI in the 2000 s increased in the western and middle-west parts of Qilian Mountains, but decreased for some areas in the eastern Qilian Mountains (Fig. 7b). These differences might be the result of spatio-temporal differences in climate change in the Qilian Mountains. Since the 2010 s, the NDVI has increased significantly for most of the study area (Fig. 7c), signaling improved vegetation grown that is consistent with the recent increase in Qinghai spruce growth in the Qilian Mountains.

4. Discussion

In this study, we found obvious increasing growth of Qinghai spruce since the 2000 s in the Qilian Mountains. Most previous dendrochronology and dendroclimatology studies in the Qilian Mountains have focused on Qilian Juniper (*Sabina przewalskii*) trees, as this long-lived tree species can be used to reconstruct past climate variations for hundreds and even thousands of years (Liu et al., 2010; Zhang et al., 2014; Gou et al., 2015). Qinghai spruce trees have received less attention. Liang et al. (2010) analyzed the spatial variability of Qinghai spruce and Qilian juniper tree growth and found that moisture availability was a dominant limiting factor for tree growth, which is consistent with our results. Li et al. (2015) found a warming-induced decline of Qinghai spruce tree growth from 1980 to 2005 using tree-ring data collected from 12 stands in the Qilian Mountains. However, the curve of mean annual basal area increment (BAI) in Li et al. (2015) shows a gently increasing trend since around the year 2000. If the tree-ring records used by Li et al. (2015) were a bit longer, the increasing trend in BAI might be clearer. Gao et al. (2015) reported increased growth of Qinghai spruce at a high elevation mesic site located in the eastern Qilian Mountains (very close to P23 in this study). There, tree growth was limited by low temperature, so a warming climate would benefit tree growth.

The increase in Qinghai spruce growth since the early 2000 s might be closely related to the recent climate changes in the study area. Based on correlations between tree-ring chronologies and climate data, we found that the growth of Qinghai spruce in the Qilian Mountains is most sensitive to conditions of limited moisture. During the period 1980–2001, temperature in the study area increased significantly while precipitation remained fairly constant. This combination induced drought stress for tree growth and resulted in the decline of Qinghai spruce growth during the 1980–2001 period. However, the warming hiatus during the 2001–2015 period, combined with increased precipitation, relieved the drought stress and promoted tree growth. This warming hiatus corresponds with the hiatus observed globally since the year 2000 (IPCC, 2013). A study by Guan et al. (2017) found that the warming hiatus produced a wetting zone over the mid-to-high latitudes of the Northern Hemisphere in recent decades, which is in line with the increase in precipitation observed in the study area. Both the warming hiatus and associated wetting trend are likely to have had significant

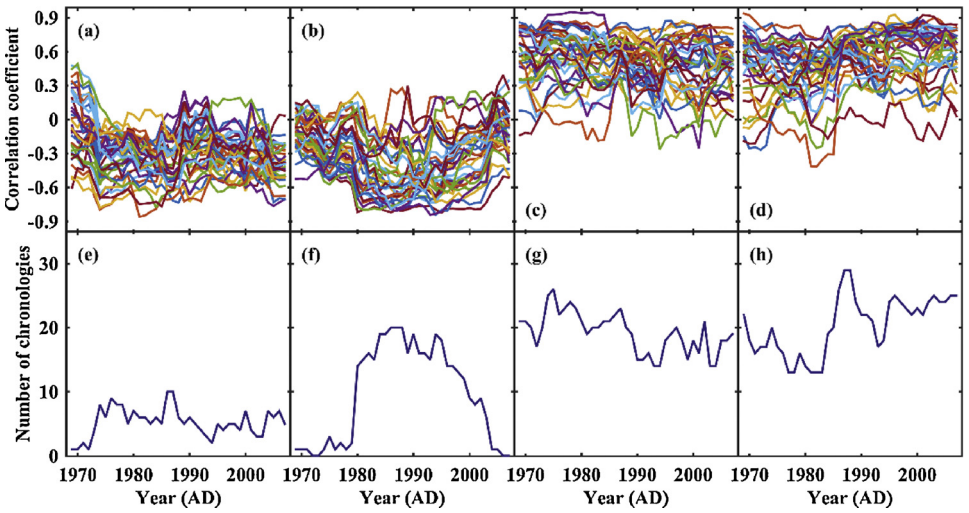

Fig. 6. The moving correlations with a 15-year window between the tree-ring chronologies and the main climatic factors limiting tree growth, namely the temperatures in prior July (a) and current June (b), the precipitation from previous year July to current year June (c), and the May-August SPEI (d). The bottom plots (e, f, g, h) indicate the number of chronologies that correlate significantly ($p < 0.05$) with the relevant climate variables for different time windows.

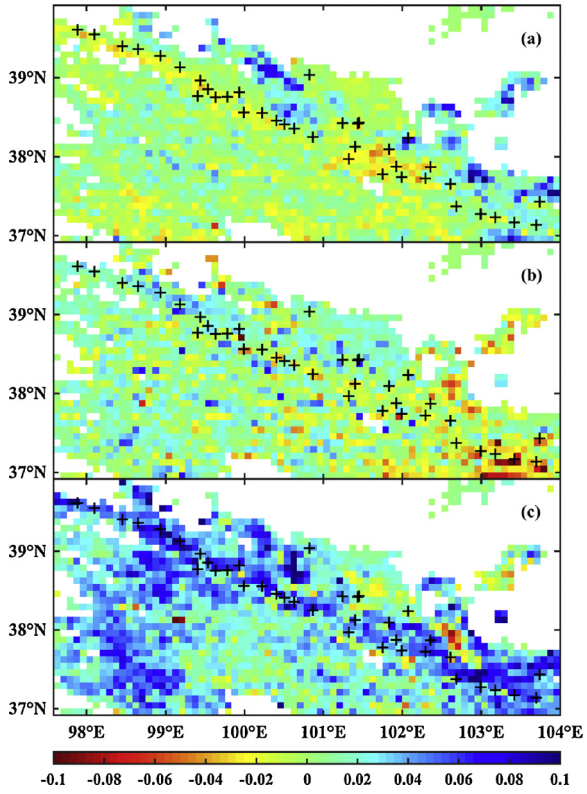

Fig. 7. The NDVI variations during 1982–2015 as calculated from the differences between NDVI values in the 1990 s and the 1980 (a), the 2000 s and the 1990 s (b), the 2010 s and the 2000 s (c). The positive values (blue colors) indicate that the NDVI increased while the negative values (red colors) indicate a decrease in the NDVI. The black crosses denote the tree-ring sampling sites.

impacts on tree and forest growth in the Northern Hemisphere, as the results of this study demonstrate.

An extended growing season would be another reason for increasing tree growth. As shown in Fig. 4d, the number of days per year with a daily mean temperature higher than 5 °C has increased by about 10 days from the period 1960–1980 to the 2000 s. A number of studies have shown that the lengthening of the growing season will accelerate tree growth, particularly for high latitude and high elevation forests (Chmielewski and Rötzer, 2001; Pretzsch et al., 2014). Although there was no monitoring data of Qinghai spruce growth phenology published in the study area, some modeling efforts have assessed the phenology and growth variations of trees' responses to climate changes. Waring and Gao (2016) simulated the tree growth of Qinghai spruce for the period 1957–2009 using a process-based forest model (3-PG model), and found that the recent reduction in the frequency of forest days in growing season related to the warming temperature can explain the increased tree growth. Yang et al. (2017) applied the Vaganov-Shashkin (VS)-oscilloscope model to study the tree-ring phenology of Qilian juniper across the Tibetan Plateau over the period 1960-2014. They found that the start of the growing season (SOS) has advanced and that the end of the growing season (EOS) has been delayed, changes that mirror regional climate changes. Changes in the phenology of trees would have a profound influence on forest growth, community structure and composition, forest ecosystems and carbon cycles, which should be carefully taken into account when making forest management decisions.

The wetter climate conditions suggested by the increased precipitation and SPEI since the 2000 s are corroborated by the NDVI, which indicates greening trend in the study area. In fact, the wetting and greening trends observed in the study area also occurred over a broader geographical region. Zhang et al. (2017a,b) found that the area, level and volume of lakes on the Tibetan Plateau decreased slightly during 1970s-1995, increased rapidly during 1996–2010, then increased at a gentle rate between 2011 and 2015. The increased net precipitation was thought to be the main driver behind the increase in lake water storage on Tibetan Plateau. In the Tianshan Mountains of northwestern China, there has been a clear increasing trend in precipitation over the past 55 years in the western and northern parts of the Tianshan Mountains (Chen et al., 2016). Piao et al. (2015) found that the climate changes had a positive impact on vegetation growth on the Qinghai-Xizang plateau. The recent greening trend will further alter the evapotranspiration, water cycle and hydroclimate (Liu et al., 2016). Overall, the combination of the warming hiatus and the wetting trend is likely to be beneficial for trees and vegetation growth throughout the arid and semi-arid areas of northwestern China.

We did not assess the impacts of increased atmospheric concentrations of CO_2 on tree growth in this study, although the effects of elevated CO_2 on tree growth is still debated. Many studies have shown that CO_2 fertilization should increase the water-use efficiency of trees, but that tree growth is often limited by soil nitrogen and other factors (Norby et al., 2010; Andreu-Hayles et al., 2011; Sleen et al., 2015). In the future studies, process-based forest models could be employed to explore the influence of CO_2 on tree growth in this area.

The warming hiatus began around the year 2000 and has lasted for 15 years. However, if the global temperatures begin to rise again, and if the wetting trend comes to an end, trees in the Qilian Mountains will likely experience drought stress again and a decline in growth. At the same time, warming is likely to prolong the growing season, which could either exacerbate drought stress or, if enough water is available, increase growth. It is still difficult to disentangle these simultaneous influences on tree growth, although a process-based forest model might be useful for resolving this problem (Landsberg, 2003; Breitenmoser et al., 2014). Changes in regional climate need to be predicated as accurately as possible, and both climate and forest models should be applied to better understand future regional climate variations and the responses of trees and forests to these changes.

5. Conclusions

In this study, we assessed Qinghai spruce tree growth and climate-growth relationships in the Qilian Mountains using tree-ring data collected from 38 forest stands. The statistical parameters of the tree-ring chronologies indicated that the trees from the western Qilian Mountains are more sensitive to climate change than those in other regions. Most of the tree-ring chronologies exhibited similar growth patterns over the past six decades, with increased growth between 1960 and 1980, followed by a decline from 1980 to 2001. There were clear increases in Qinghai spruce growth in the Qilian Mountains since the 2000 s, a finding that has not been reported by any previous studies. Temperature increased dramatically in the study area during the 1980–2001 period, whereas precipitation decreased only slightly. The warming therefore resulted in drought stress and hence a decline in tree growth during this period. Since the early 2000 s, warming has slowed, and precipitation has increased in the Qilian Mountains. The decreased correlations between tree-ring chronologies and temperature and SPEI suggest that the drought stress trees experienced between 1980 and 2001 has been mitigated in the last 15 years. The prolonged growing season might be another reason for the increased tree growth. The recent wetting trend has benefitted regional vegetation growth, as shown by the increasing NDVI. The increase in tree growth and greening trend should be considered in climate and forest model, as it will affect the accuracy of simulations. Meanwhile, climate models and forest process-based models should be employed in future studies to help us predict both future changes in climate and how forests respond to these changes.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agrformet.2018.05.025.

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